Best Focus Shift Mitigation for Extending the Depth of Focus

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ABSTRACT

The low-k_1 domain of immersion lithography tends to result in much smaller depths of focus (DoF) compared to prior technology nodes. For 28 nm technology and beyond it is a challenge since (metal) layers have to deal with a wide range of structures. Beside the high variety of features, the reticle induced (mask 3D) effects became non-negligible. These mask 3D effects lead to best focus shift. In order to enhance the overlapping DoF, so called usable DoF (uDoF), alignment of each individual features best focus is required. So means the mitigation of the best focus shift.

This study investigates the impact of mask 3D effects and the ability to correct the wavefront in order to extend the uDoF. The generation of the wavefront correction map is possible by using computational lithographic such Tachyon simulations software (from Brion). And inside the scanner the wavefront optimization is feasible by applying a projection lens modulator, FlexWave™ (by ASML). This study explores both the computational lithography and scanner wavefront correction capabilities.

In the first part of this work, simulations are conducted based on the determination and mitigation of best focus shift (coming from mask 3D effects) so as to improve the uDoF. In order to validate the feasibility of best focus shift decrease by wavefront tuning and mitigation results, the wavefront optimization provided correction maps are introduced into a rigorous simulator. Finally these results on best focus shift and uDoF are compared to wafers exposed using FlexWave then measured by scanning electron microscopy (SEM).

Keywords: Best Focus Shift, Depth of Focus, Tachyon SMO-FW, FlexWave™, Scanning Electron Microscopy (SEM)

1. INTRODUCTION

In order to fulfill the increasing demand for 28 nm design rule devices, a number of new and existing lithography techniques have been developed and put on production. In this low k_1 domain, the DoF is limited compared to prior technology nodes. This limitation turns out to be more problematic when there is a wide range of different 1D and 2D structures, as is the case for metal layers. For these layers the uDoF is further constrained due to mask effects and the structure dependence of the best focus. So the mitigation of the best focus shift due to mask topology enables uDoF improvement.

RET (Resolution Enhancement Techniques) can be a solution to extend the uDoF. They allow a high fidelity mask-to silicon transfer thus an extension of optical lithography in the low-k_1 domain. These techniques most usually include off-axis illumination, phase-shifting masks (PSM) and OPC (Optical proximity Correction). OPC is widely used to compensate for lithography process proximity effects – modification of the shapes at the mask level by applying models that have the capability of predicting printing at the wafer level.

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Within the frame of RET optical simulations, the computational process time duration for mask simulation is a challenge. Therefore to reduce the process time, approximation methods are applied in a production flow for simulations near the mask. The most commonly used method is the thin-mask model, also called the Kirchhoff approximation, which considers the mask thickness to be negligible and infinitely thin. This approximation has the advantage of mathematical simplicity in terms of implementation into OPC simulations. However because it is a scalar method, it has limitations compared to rigorous methods which apply vectorial calculations [1].

The Kirchhoff approximation correctly works until the features size of the mask approaches the 193 nm optical wavelength of the exposure system. For printable feature sizes needed at the 2x nm node the mask thickness cannot be ignored anymore. The so called mask 3D (M3D) effect, which leads to best focus shift, contrast degradation, difference of the diffraction intensity comes in to play.

This paper focuses on diminution of best focus shift with the aim to find a way to improve the uDoF. The used approach includes RET/OPC solutions using computational lithographic and the FlexWave lens modulator within the scanner. This paper includes a short description of the theoretical M3D effects on best focus and FlexWave. This is then followed by experiment methods and results which are split into two main parts: simulation related work and validation by process:

> *In the first section*, based on computational lithography/RET; an approach is investigated for best focus shift mitigation by correcting the wavefront in order to compensate for the mask 3D effects with Brion Tachyon software. This work consists of three steps: a) simulation of the focus shift b) mitigation by wavefront modification and c) feasibility by using rigorous lithographic simulation with Panoramic® software.
>
> *In the second section,* based on exposed wafer analysis, simulation data is compared with scanning electron microscopy (SEM) measurements on proceeded wafers using FlexWave.

2. EFFECTS OF THREE-DIMENSIONAL MASK TOPOLOGY ON FOCUS

Light diffraction rigorous modeling of the mask was introduced by A. Wong by illustrating and explaining important mask 3D effects [2]. Since then numerous studies were accomplished; particularly with high NA lithography.

The basis of M3D is to recognize that masks have a non-negligible thickness or topography. This topography can be described by a set of parameters (optical index; thickness of the absorber etc.). These mask 3D effects are approached or determined by mask diffraction analysis as they are mainly caused by light diffractions [3][4], which occur at the edge of structures at mask level.

These topological effects are responsible for the difference in phase of the diffracted orders due to asymmetry between them [5]. This fact implies the delta best focus difference of the variety of structures. Further investigation of the delta phase assignment on line-versus-pitch structures has already showed that the phase difference of the diffracted orders have a corresponding phenomenon to the one induced by wavefront aberrations of the projection optics [3]. The mask 3D effects can thus be compensated for by wavefront optimization.

3. THE FLEXWAVE MANIPULATOR

A possible solution to handle some of the mask 3D effects can be the application of the FlexWave lens manipulator available in ASML scanners.

The latest generation NXT: 1950i systems have the FlexWave optical element manipulator (see Figure 1). This advanced actuator allows the adjustment of the wavefront to compensate for process induced effects, like M3D effects, which can be responsible for focus and pattern shifts. This module is composed of two optical elements placed near the projection lens pupil plane. They consist of individually heated segments translating into a change in optical path length as a function of the position. It allows the adjustment of higher order aberration terms and tuning the phase of the wavefront. This phase wavefront change in the projection pupil can thus mitigate M3D effects.

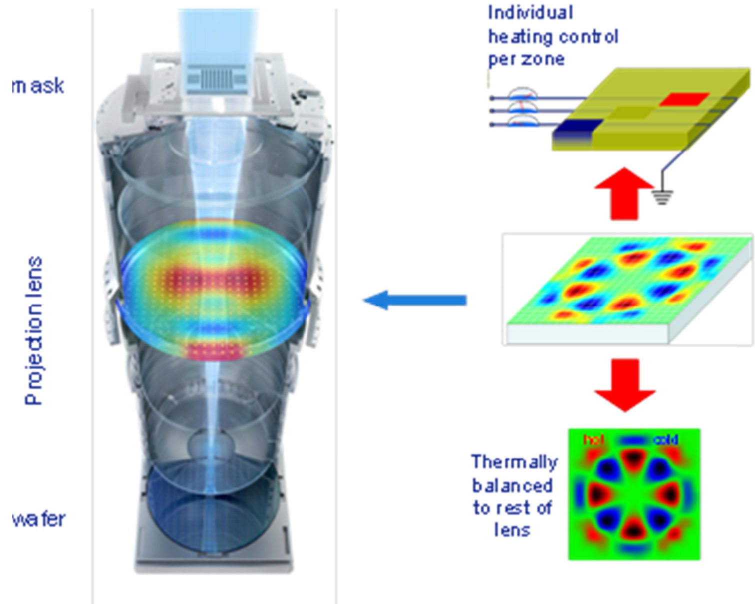


Figure 1: The principle of the FlexWave optical element manipulator available in ASML NXT: 1950i scanner; placed near the projection lens pupil plane; depicted here by a plane-parallel optical plate consisting individual heating segments

Besides reducing the M3D effect, the FlexWave module can also minimize the overlay error performance of the scanner and better control lens heating that can occur over time (these possibilities are not exploited within the frame of this study).

Reducing the best focus differences and thus improving the overlapping DoF has been already analyzed [6]. By applying a specific application wavefront, it can correct up to 50% of the best focus differences based on SEM measurement analysis.

Tachyon source mask optimization (SMO) based simulations are used to generate the pupil wavefront required as input for FlexWave. This SMO-FlexWave (SMO-FW) module is optimizing the wavefront for a set of structures defined by the user. Two ways are proposed to realize the optimization flow: one is source mask optimization with wavefront optimization; the other is only wavefront optimization with a fixed mask and fixed illumination. This second option can be suitable for wavefront tuning in a manufacturing environment [7]. This work is based on the only wavefront optimization with an already optimized mask and illumination source by OPC.

4. SIMULATION EXPERIMENTS AND RESULTS

As described earlier this section is dedicated to computational wavefront optimization for the feasibility of uDoF improvement by decreasing the best focus dispersion.

4.1 Experimental setup

These simulation experiments are carried out on a 28 nm Metal layer using an ASML NXT:1950i scanner (4X reduction immersion lithography exposure system with a wavelength λ=193 nm and numerical aperture NA=1.35). The Tachyon computational lithography platform (Tachyon SMO-FW software for RET) is used for optimization in this study. The simulation experiments are split into two parts regarding the illumination modes (both XY polarized): Annular (σ_{outer} = 0.9; σ_{inner} = 0.7) and C-Quad (σ_{outer} = 0.8; σ_{inner} = 0.6). The reason to split the experiments in to two parts, from the point of view illumination modes, is that the utilization of C-Quad illumination can result in more important effects.

Regarding the structures selection serving for wavefront correction map generation: Table 1 includes 1D and 2D features which will be called calibration features in the following part of the paper (these are the most focus sensitive features from a previous focus shift study).

Table 1: Information on selected 1D and 2D calibration structures for the simulations

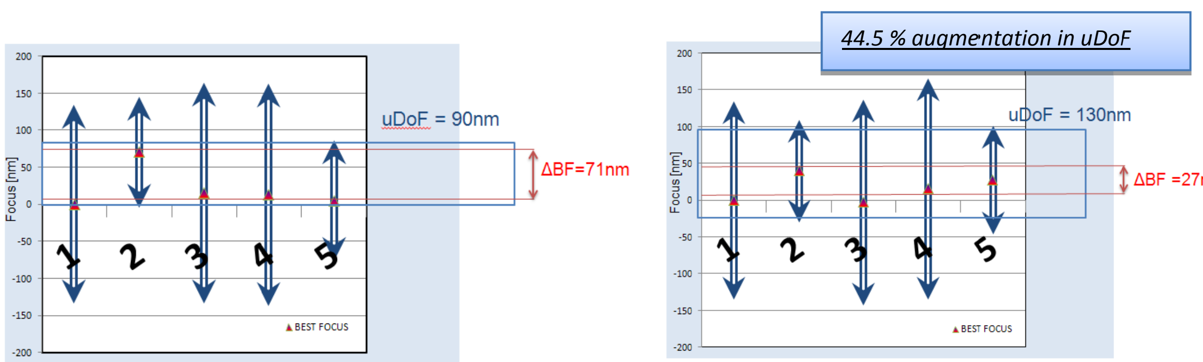
	Test structure	*Structure Notation*		*Test structure*	*Structure Notation*
1D	Dense	1	2D	Line End	6
	3 Lines_Pitch A	2		2D_A	7
	3 Lines_ Pitch B	3		2D_B	8
	2 Lines	4			
	4 Lines	5			

So the following four sets of wavefront optimizations are performed:

1. Illumination mode : C-Quad ($\sigma_{outer} = 0.8$; $\sigma_{inner} = 0.6$)
    a. on 1D calibration features
    b. on 2D calibration features
2. Illumination mode : Annular ($\sigma_{outer} = 0.9$; $\sigma_{inner} = 0.7$)
    a. on 1D calibration features
    b. on 2D calibration features

4.2 Results

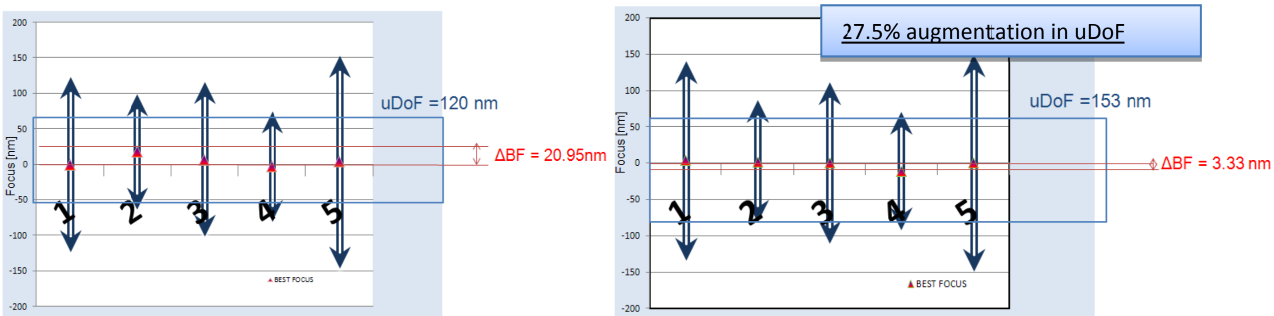
As the starting point of the study, experiments are conducted on 1D calibration structures. The results, based on the sets of five 1D calibration structures, are shown in the figures below (Figure 2 and 3). Figure 2 represents simulation results with setup for C-Quad illumination mode while Figure 3 is for the setup for Annular illumination.



(a) (b)

Figure 2: : C-Quad illumination mode (a) uDoF and delta Best Focus *before* wavefront optimization on 1D calibration structures (b) uDoF and delta Best Focus *after* wavefront optimization on 1D calibration structures

First the setup with C-Quad illumination on 1D calibration strucures is analyzed. Figure 2 (a) shows a snapshot without wavefront correction map and (b) with the correction map. These figures indicate the best focus (red triangles) and the DoF (blue arrows) for each 1D calibration structures (see notation in Table 1). The best focus dispersion is minimized after the optimization of the wavefront. So that makes the uDoF *augmented by 44.5%.*



(a) (b)

Figure 3: : Annular illumination mode (a) uDoF and delta Best Focus *before* wavefront optimization on 1D calibration structures (b) uDoF and delta Best Focus *after* wavefront optimization on 1D calibration structures

Figure 3 corresponds to setup with Annular illumination on 1D calibration structures. Figure 3 represents the analyzed simulation data in the same manner, where the left (a) image indicates the snapshot without wavefront optimisation and the right one (b) shows a snapshot by employing the correction map. Best focus and DoF of each calibration structures are represented similar to Figure 2. In this case there also is a noticeable amount of mitigation in delta best focus, though weaker than the previous case, which can be the fact that Annular illumination source was applied. A re-centering of best focus is observed, thus a *27.5% extension* in uDoF due to wavefront tuning is achievable.

The summarized results from the experiments using Tachyon SMO-FW simulations are shown in Table 2 for the delta best focus and Table 3 for the uDoF. Data reported here are including in additional results from optimizations on 2D calibration features with both illumination modes.

Table 2: Delta best focus dispersion from Tachyon SMO-FW simulation on the four calibration sets

Illumination mode	Calibration structure type for correction map generation	ΔBF [nm] Before SMO FW	ΔBF [nm] After SMO FW
C-Quad	1D	71	26
	2D	12	1
Annular	1D	20.9	3.3
	2D	13.1	2.6

Table 3: The uDoF from Tachyon SMO-FW simulation on the four calibration sets

Illumination mode	Calibration structure type for correction map generation	uDOF [nm] Before SMO FW	uDOF [nm] After SMO FW	Percentage [%] of uDoF augmentation
C Quad	1D	90	130	**44.5**
	2D	122	134	**9.9**
Annular	1D	120	153	**27.5**
	2D	60	72	**20**

Table 2 shows pronounced best focus dispersions before wavefront tuning, which are reduced after the optimization. As consequence the overlapping DoF (see Table 3) of the whole set of calibration structures improves (up to 44.5%). These results drive further study in to the use of the FlexWave module to explore its effects, which are validated mainly by SEM measurements.

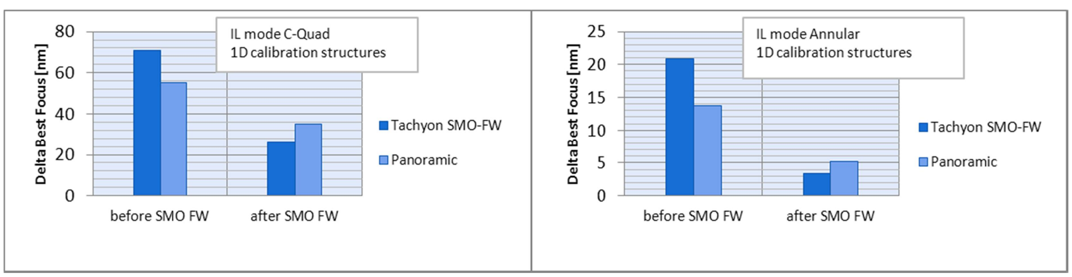
4.3 Method of validation by rigorous simulation

The purpose of this validation is the feasibility of focus shift decrease by wavefront tuning by rigorous computational lithography. The evaluation is performed on the calibration structures by using the capabilities of the Panoramic Technology® simulation package. The FlexWave correction maps (or more specifically the Zernike coefficients), the output data from Tachyon are used. These FlexWave correction maps consist in information of the wavefront specified with 64 Zernike coefficients which are introduced as input.

The impact of the utilization of the wavefront map is estimated assuming the same structures and illumination conditions as applied in the Tachyon SMO-FW M3D simulations. The result shows a same trend as in the previous section for the Tachyon SMO-FW simulation. They are reported below:

Table 4: Delta best focus dispersion from Panoramic® simulation on the four set of calibration structures; *NA means that that it was not possible to investigate further for the validation of wavefront correction map on 2D calibration features (C-Quad illumination mode), since there is a limitation of resolution.

Illumination mode	Calibration structure type for correction map generation	ΔBF [nm] without wavefront optimization	ΔBF [nm] with wavefront optimization
C-Quad	1D	55	35
	2D	NA*	NA*
Annular	1D	13.71	5.20
	2D	20	5



(a) (b)

Figure 4: Delta Best Focus comparison (a) for C-Quad illumination mode (b) for Annular illumination mode; illustrating the difference before and after wavefront optimization by Tachyon SMO-FW M3D and Panoramic®; simulation results based on 1D calibration structures

Figure 4 (a) with setup for C-Quad illumination mode and (b) with setup for Annular illumination mode illustrates clearly the comparable tendency between the Tachyon SMO-FW and Panoramic® software simulations by indicating the status without and with wavefront optimization for the delta best focus.

5. VALIDATION BY EXPOSED WAFERS' MEASUREMENT ANALYSIS

Wafers are performed using FlexWave on an ASML NXT:1950i scanner through dose and focus to confirm the simulation results and to check the impact on silicon. Here we used the generated wavefront correction maps (based on the Tachyon SMO-FW M3D simulations) as input data into the scanner. Two additional wafers are processed without any correction maps serving as references. Measurements are realized by scanning electron microscopy (SEM).

In this evaluation on processed wafers, the SEM measurement data are split into:

1. Evaluation of the simulation on calibration structures
2. Evaluation on non-calibration structures

The SEM measurements analyses consisted mainly of process windows (PW) and Bossung curves analysis.

5.1 SEM measurements analysis on calibration features

As a starting point, to combine simulated and measured results, the calibration structures are analyzed by full-map SEM measurements. The table below shows the study on calibration features with the difference in best focus dispersion before and after optimization:

Table 5: SEM analysis results on proceeded wafers

Illumination mode	Calibration structure type for correction map generation	ΔBF [nm] without FW	ΔBF [nm] with FW
C-Quad	1D	28.9	10.1
	2D	16.6	3.5
Annular	1D	27.7	6.7
	2D	14.3	11.1

Table 5 clearly shows an impact in best focus shift for the calibration features: a noticeable decrease can be observed. The best focus of each calibration structure demonstrates improvements on alignment, which also have uDoF impact as follows:

1. At C-Quad Illumination mode; an augmentation of uDoF approximately from 60 nm to 110 nm (with the wavefront correction map generated on the 1D calibration features) ; from 60 nm to 90nm (with the wavefront correction map generated on the 2D calibration features)
2. At Annular Illumination mode; an extension of uDoF approximately from 80 nm to 120 nm (with the wavefront correction map generated on the 1D calibration features); from 80 nm to 110 nm (with the wavefront correction map generated on the 2D calibration features)

These results show tight correlation with Tachyon SMO-FW simulation results.

5.2 SEM measurements analysis on non-calibration features

Within this section, the goal is the inspection of the impact on additional set of features (beyond the calibration structures) that were not served to optimize the wavefront; therefore to explore the validity of the optimization. Beside the validation of the optimization the objective of this analysis is the choice of calibration structures.

This analysis includes a set of 21 features. A similar trend can be observed: the best focus of each individual structure is re-centered reducing the overall dispersion of best focus (Table 6 below).

Table 6: SEM analysis results on proceeded wafers

Illumination mode	Calibration structure type for correction map generation	ΔBF [nm] without FW	ΔBF [nm] with FW
C-Quad	1D	47.10	26
	2D	47.10	30.2
Annular	1D	41.60	12.7
	2D	41.60	31.5

Table 6 clearly shows the impact of the application of wavefront tuning using FlexWave, reducing the best focus dispersion. Along the best focus mitigation a noticeable augmentation can be observed in uDoF:

1. At C-Quad Illumination mode, an augmentation of uDoF approximately from 80 nm up to 110 nm (for both the generated wavefront maps on the 1D and 2D calibration structures)
2. At Annular Illumination mode, an extension of uDoF approximately from 60 to 110 nm (for the wavefront map generated on 1D calibration structures) and nearly from 60 to 90 nm (for the wavefront map generated on 2D calibration structures)

With the aim of investigation on calibration structures selection, the validation on additional features is completed by checking the possible penalties derived from the application of wavefront tuning. Along the SEM measurements analysis, no remarkable degradation can be observed. Furthermore the application of the correction map, generated on 1D calibration structures, shows more significant reduction in delta best focus. So means that for further improvements on calibration structure selection: the focus is on 1D features regarding measurement feasibility/complexity aspect.

5.3 SEM measurements analysis on hotspots

Finally, in order to explore the impact of wavefront tuning by FlexWave on metal 28 nm hotspots, a set of hotspots structures is chosen from production full-chip verification using Tachyon Lithographic Manufacturing Check (LMC) simulations. Tachyon LMC is a RET verification software solution that can provide the most critical spots including bridging and necking defects. Note that these LMC simulations are not the same for Annular and C-Quad illumination sources, thus different hotspots are checked for the two different illumination sources. These experiments consist of bridging and necking defects with overall about ten hotspots for each case. At the chip level measurements are performed by SEM on the whole wafer. Focus shift analysis is addressed first to assess whether applying the correction map using FlexWave re-centers best focus. In parallel the impact on uDoF improvement is investigated.

The study of these critical defects is not obvious; the extraction of the results is complex: a reliable determination of the best focus and uDoF cannot be made automatically. A commonly applied method is visual analysis – these results are handled this way. As such there might be an offset between SEM measured and simulated data due to measurement data quality (which can always be the case for all SEM measurements).

These results corroborate the computational wavefront optimization in that the overlapping process window is improved: the position of the best focuses is re-centered (Figure 5 below) for checked hotspots thus uDoF is extended:

1. At C-Quad Illumination mode, the best focus dispersion on the chosen hotpots decreased from around 30 nm to 10 nm (same as for both the applied wavefront map generated on 1D and 2D calibration structures); and an augmentation of uDoF from 60 nm up to 90 nm
2. Using Annular Illumination, best focus mitigation of 60 nm to 30 nm is achieved (using the wavefront map generated on 1D calibration structures) and to 20 nm (with the wavefront map generated on 2D calibration structures) ; and an extension of uDoF approximately from 60 to 80 nm

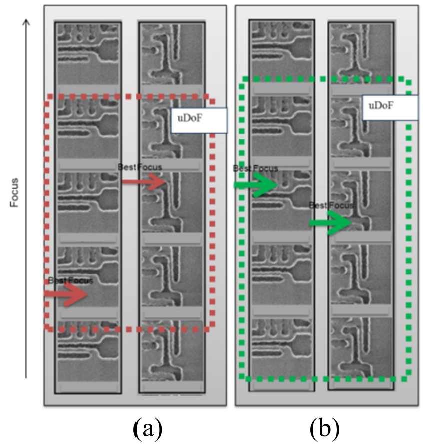


Figure 5: Illumination mode: C-Quad; Example of the wavefront optimization impact on metal 28 nm hotspots bridging at best dose illustrating the re-centered best focus position and evaluated uDoF for taken hotspots (a) without FW (b) with FW

Overall, according to these data, the hotspot evaluation showed close correlation between SEM measurements data and simulation data from Tachyon SMO-FW.

6. CONCLUSION

In this paper the compensation of mask 3D effects by correction of the wavefront based on the application of FlexWave is investigated. According to the performed wavefront optimization using computational lithography and SEM measurements analysis there is a noticeable effect from the mask topography. The wavefront manipulator tool enabled an imaging enhancement by minimizing mask topographic effects.

Based on comparative analysis on 28 nm metal layer of computational lithography and SEM measurements data, consistent results were found. By presented experiments it was shown that both by computational lithography and scanner side that an increase up to 45% in uDoF can be achieved by applying wavefront optimization.

Beyond the exploitation of uDoF enhancement, investigation was performed in order to assist calibration features selection. Here we found that 1D features are the best candidates to serve for wavefront correction map generation. However it should be noted that there is a limitation of calibration feature selection to determine focus shift sensitivity since it is still a challenge. Potential further improvements are on-going at this point.

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